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# An evaluation of plasmon frequency associated with charge carriers for heavy electron systems

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**Abstracts** : We present an evaluation of the plasmon frequency associated with charge carriers of heavy electron systems using the theoretical model of Millis, Lavagna and Lee. For such systems, there are two types of plasmon frequencies – one is related with the uncorrelated conduction electrons which gives high plasmon frequency, and the other is low plasmon frequency which depends upon the Fermi temperature $T_f$ and the total carrier density $n$ which is the sum of the carrier densities $n_c$ and $n_f$ due to conduction and $f$-electrons respectively.

**Keyowrds** : Plasmon frequency, uncorrelated conduction electrons, Fermi temperature, heavy electron systems.

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## 1. Introduction

Heavy electron systems are electrically conducting materials with peculiar low temperature properties that distinguish them from ordinary metals [1,2].

In these systems there are two types of electrons :

(i) Conduction electrons whose role is dominant below Fermi temperature $T_F$;

(ii) $f$-electrons whose role is dominant above $T_F$.

At high temperature, these systems behave as a weakly interacting collection of $f$-electron moments and conduction electrons with quite ordinary masses. At low temperatures, the $f$-electron moments become strongly coupled to the conduction electrons and to one another, and the conduction electron effective mass ($m^*$) is 10 to 100 times larger the bare electron mass ($m$). The enhancement of the effective mass

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can be assigned to the presence of localized *f* electrons in all heavy electron systems. These may be Ce ions with 4*f* electrons or U or Np ions with 5*f* electrons. Prominent examples are $CeAl_3$, $CeCu_2Si_2$, $CeCu_6$, $UBe_{13}$, $UPt_3$, $UCd_{11}$, $U_2Zn_{17}$ and $NpBe_{13}$. The 4*f* or 5*f* electrons interacting with the bands of the delocalized electrons (*d* or *s*) can be considered as the "heavy electron" [3,4] of these systems. For the electromagnetic response of heavy electron systems, the optical experiments and the analysis of the experimental data give the value of the scattering rate and the plasmon frequency associated with the charge carriers. For $CeAl_3$, Awasthi [5] have obtained the real part of optical conductivity $\sigma(\omega)$ [$= \sigma_1(\omega) + i\sigma_2(\omega)$] from Kramers-Kronig analysis of the excitation spectrum data.

In this paper, we report the evaluation of the plasmon frequency of various heavy electron systems. These systems possess two types of plasma frequency [6,7]. One is the high plasma frequency and is concerned with the uncorrelated conduction electrons. The other is the low plasma frequency and depends upon the Fermi temperature $T_F$ and the total carrier density $n$ ($= n_c + n_f$), where $n$ and $n_f$ are carrier densities due to conduction and *f* electrons respectively.

## 2. Method of calculation

We have used the theoretical formulation of Millis *et al* [6,7] which is based on a study of the low temperature properties of the lattice Anderson Hamiltonian, in the Kondo limit. It describes a band of nearly free electrons hybridizing with a very highly correlated band of electrons. In the absence of this hybridization, each *f* electron is confined to one lattice site localized orbitals which are far below the Fermi energy. This model is believed to contain the essential physics of heavy electron systems. It has a nonmagnetic ground state that behaves like a Fermi liquid with large effective mass.

For the evaluation of $\sigma(\omega, T)$, scattering must be taken into account. There are two possible sources of scattering of electrons in these systems. One is the scattering of electrons from the impurities and the other is the scattering from boson fluctuations. This latter turns out to be in some ways analogous to electron-phonon scattering. One can apply Matthiesen's rule [8] in which the resistivities due to different scattering mechanism are to be added. Thus, if in the presence of impurities only the conductivity is $\sigma_i$ and in the presence of boson only the conductivity is $\sigma_b$ then the total conductivity is given by

$$\sigma^{-1} = \sigma_i^{-1} + \sigma_b^{-1}. \tag{1}$$

Matthiessen's rule is believed to be valid when the various scattering mechanism are not momentum dependent and are weak.

At sufficiently low temperatures, only impurity-scattering is relevant. To compute the corresponding impurity component $\sigma_i(\omega, T)$ of $\sigma(\omega, T)$, the disorder must be coupled into the system. Millis and Lee [6] obtained

$$\sigma_l(\omega) = \left[ne^2/m_b\right]\left[\tau_l/\left\{1+(m^*/m_b)^2\,\omega^2\tau_l^2\right\}\right]$$

$$= \left[ne^2/m^*\right]\left[\tau_l^*/\left\{1+\left(\omega\tau_l^*\right)^2\right\}\right] \quad (2)$$

introducing the definition, $\tau_l^*/\tau_l = m^*/m$.

Freytag and Keller [9] calculated the dynamical conductivity for heavy electron systems, taking into account the effect of impurity scattering within a mean field approximation of the Anderson Hamiltonian They obtained a dynamical conductivity characterized by a narrow low-frequency - Drude peak superimposed on a broad background with a minimum near $k_B T_k$ presumably due to a mixture of the broadened interband transition and the Drude behaviour of the conduction electrons Two characteristic plasma frequencies are then expected . the one at high frequency is given by

$$\omega_p^2 = 4\pi n_c e^2/m_b. \quad (3)$$

This identifies the uncorrected conduction electrons. The other is at low frequency and associated with the heavy plasmons, given by

$$\varpi_p^* = \sqrt{\left[6\left(1+n_f/n_c\right)\right]\times T^*}, \quad (4)$$

where $T^*$ is the renormalized Fermi temperature (usually identified with $T_k$) and $n_c$ and $n_f$ are the carrier densities due to conduction and $f$ electrons respectively

To include the scattering from bosons ($\sigma_b$), application of Matthiessen's rule leads to the result that the conductivity is simply formed by adding the $c$-electron self-energy due to electron-boson interactions. Moreover, because the $f$ electrons are dispersionless in this approach, the applied model is not Galilean invariant. Keeping in mind that the umklapp process can occur at all nonzero temperatures and interpreting the imaginary part of the $c$-electron self-energy as a temperature and frequency-dependent scattering rate $1/2\pi\tau(\omega,T)$. Millis and Lee [6] found

$$1/\tau(\omega,T) = 1/\tau_l + (m^*/Nm_b)\cdot(\omega^2+\pi^2T^2)/\varepsilon_f. \quad (5)$$

At $T = 0$, and for $\omega < \omega_c$, where

$$\omega_c^2 = N\varepsilon_f(m_b/m^*)/\tau_l, \quad (6)$$

the impurity scattering dominates and eq. (2) applies. For larger $\omega$, one finds

$$\sigma_1(\omega) \sim \sigma_b \sim (ne^2/m_b)\left(1/N(m^* \;\; m_b\right)\varepsilon_f \sim ne^2/m_bW. \quad (7)$$

Therefore for $\omega > \omega_c$ the conductivity becomes very small and approximately independent of frequency.

Now consider the case $T = 0$, and $\omega = 0$. The resistivity $\rho = \sigma^{-1}$ and after averaging eq. (5) over the energies of thermally excited electrons, one gets

$$\rho = \left(m_b/ne^2\right)\left(1/\tau + 4m^*\pi^2T^2/3Nm_b\epsilon_f\right). \tag{8}$$

## 3. Results and discussion

We have calculated the plasma frequency of different heavy-electron-systems using the two relations given in eqs. (3) and (4), at the renormalized Fermi temperature $T^*$. The heavy electron plasmon mode reflects not only the heavy quasiparticle mass $(m^*/m)$ but also the renormalized Coulomb screening The other plasmon frequency is the unscreened heavy plasmon and is associated with the spectral weight functions and narrow Drude like behaviour of the conduction electrons. The results are given in Table 1 where the calculated ratio of the effective mass to ordinary mass of the electron in these heavy-electron-systems are also given.

**Table 1.** Plasmon frequency of different heavy electron systems

| Heavy electron systems | $m^*/m$ | $\omega_p^*$(eV) using eq (3) | $\omega_p^*$(eV) using eq (4) | $T^*$ (Kelvin) |
|---|---|---|---|---|
| $CeCu_2Si_2$ | 220 | 9 371 | 10 446 | 11 340 |
| $CeAl_3$ | 1620 | 3 453 | 4 204 | 4 564 |
| $CeCu_6$ | 1300 | 3 856 | 4 053 | 4 400 |
| $CePd_3$ | 370 | 6 412 | 7 559 | 8 210 |
| $UPt_3$ | 450 | 6 552 | 5 296 | 5 700 |
| $UBe_{13}$ | 1100 | 1 756 | 2 361 | 2 560 |
| $URu_2Si_2$ | 180 | 11 073 | 9 563 | 10 380 |
| $UCu_5$ | 250 | 8.790 | 7 344 | 7.974 |
| $U_2Zn_{17}$ | 500 | 6 216 | 6 519 | 7 07 |
| $UPd_2Al_3$ | 150 | 11 348 | 12 698 | 13 79 |

We have also studied the temperature dependence of resistivity $\rho(T)$ for two heavy-electron-systems $UPt_3$ and $CeAl_3$ and have been calculated using eq. (8), and are given in Table 2 from 5 to 300 K. The $CeAl_3$ compound has a hexagonal crystal structure and its resistivity displays $T^2$ dependence up to $T = 0.3$ K. Our calculation gives $\rho_0 = 0.95$ $\mu\Omega$ cm. The experimental value [10] is $\rho_0 = 0.76$ $\mu\Omega$ cm. The actinide $UPt_3$ also has a hexagonal structure and displays an anisotropic resistivity. The resistivity is different for *ab* plane and along the hexagonal *c* axis. It is also found to follow the $T^2$ behaviour. Our calculated results for $UPt_3$ for *c* axis are very much near to $[\rho(T)]_{exp}$ at *c*-axis.

Table 2. Temperature dependence of resistivity $\rho(T)$ for $UPt_3$ and $CeAl_3$

| $T$ (Kelvin) | $\rho(T)$ for $UPt_3$ ($\mu\Omega$ cm) | $\rho(T)$ for $CeAl_3$ ($\mu\Omega$ cm) | $T$ (Kelvin) | $\rho(T)$ for $UPt_3$ ($\mu\Omega$ cm) | $\rho(T)$ for $CeAl_3$ ($\mu\Omega$ cm) |
|---|---|---|---|---|---|
| 5 | 12 6 | 150 2 | 190 | 88 5 | 160 5 |
| 10 | 21 2 | 162 6 | 200 | 90 2 | 158 2 |
| 50 | 32 8 | 210 8 | 220 | 92 0 | 156 0 |
| 100 | 78 3 | 200 5 | 240 | 94 3 | 153 9 |
| 150 | 80 4 | 180 4 | 260 | 96 5 | 150 2 |
| 160 | 82 6 | 172 4 | 280 | 97 2 | 148 0 |
| 170 | 84 5 | 168 3 | 300 | 99 8 | 147 0 |
| 180 | 86 2 | 164 6 | | | |

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## References

[1] H R Otto, H Rudigier, P Delsing and Z Fisk *Phys Rev Lett* **55** 1595 (1985)

[2] Z Fisk, D W Hess, C J Pethick, D Pines, J L Smith, J D Thompson and J O Willis *Science* **239** 33 (1988)

[3] P A Lee, T M Rice, J W Serene, L J Sham and J W Wilkins *Comments Condens Matter Phys* **12** 99 (1986)

[4] T M Rice *Phys Scr* **T19** 246 (1987)

[5] A M Awasthi, L. Degiorgi, G Gruner, Y Dalichaouch and M B Maple *Phys Rev* **B48** 10692 (1993)

[6] A J Millis and P A Lee *Phys Rev* **B35** 3394 (1987)

[7] A J Millis, M Lavagna and P A Lee *Phys Rev* **B36** 864 (1987)

[8] N W Ashcroft and N D Mermin *Solid State Physics* p 323 (India Harcourt Asia PTE Ltd ) (2001)

[9] R Freytag and J Keller *Z Phys* **B80** 241 (1990)